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NIST Technical Note 1410

Measuring Long Gage Blocks With the NIST Line Scale Interferometer

John S. Beers

QC
100
U5753
NO.1410
1995

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May 1995

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National Institute of Standards
and Technology
Technical Note 1410
Natl. Inst. Stand. Technol.
Tech. Note 1410
20 pages (May 1995)
CODEN: NTNOEF

U.S. Government Printing Office
Washington: 1995

For sale by the Superintendent of
Documents
U.S. Government Printing Office
Washington, DC 20402

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Measuring Long Gage Blocks with the NIST Line Scale Interferometer

By John S. Beers

An improved method for temporarily converting long gage blocks into line scales is described. The new process employs fused silica rather than previously used steel conversion gage blocks. Conversion blocks are pairs of small (13 mm) gage blocks with graduation lines on their side faces. When the pair is wrung to a long gage block, one at each end with the graduated faces upward, the long block becomes a line scale. Converted blocks can be measured by fringe counting (dynamic) interferometry in the NIST line scale interferometer. This measurement can serve as an independent long block measurement, or it can be used to establish the order of interference for measuring a long block by single wavelength static interferometry. The new conversion blocks have several advantages as shown by experimental evidence. Measurement uncertainties of the static and dynamic interferometric processes are compared.

Key Words: Length; gage blocks; line scales; interferometry; uncertainty.

1. Introduction

Gage blocks are linear dimensional standards where the length interval is defined as the distance between opposing, optically flat and parallel, end faces. Line scales are linear standards using graduations to define lengths (e.g., meter bars and microscope magnification standards). Both these forms are widely used in industry to maintain dimensional control in manufacturing processes ranging from micro-miniature electronic circuits to aircraft. The key to their utility lies in the ability to relate them precisely to the international standard of length[1] by interferometry using laser light of known frequency. At NIST, static interferometry[2] (stationary optical components and stationary interference fringe pattern) is used to measure gage blocks and dynamic interferometry[3] (fringe counting with a moving reflector) is used for measuring line scales.

A method will be described here for temporarily converting gage blocks into line scales so they can be measured by the dynamic process. There are advantages and needs for occasional use of this method to measure blocks over 100 mm long.

Long gage blocks are made of steel and have flat and parallel opposing faces. These optically lapped gaging faces can be "wrung", i.e., they can be brought into such close contact that they will adhere tightly together, separated only by an oil or light grease wringing film usually less than 0.025 μm thick. This property makes it possible to combine gage blocks into nearly any length up to 250

length up to 250 mm from a standard set of 88 blocks in scaled lengths from 0.5 mm to 100 mm. Supplementing these sets with long-block sets of 8 scaled lengths from 125 mm to 500 mm greatly extends the range.

Precision line scales come in many forms. Some are metal, usually steel or Invar, where the lines are machine ruled with diamond points. Others are transparent materials such as glass or fused silica with deposited chromium rulings. Line widths from less than 1 μm to 10 μm or more and spacings (line center to line center) from 1 μm up to 1 m or more are available.

Converting a selected gage block into a line scale is accomplished with a pair of small conversion gage blocks having graduations on their non-gaging faces as shown in Figure 1. The two conversion blocks are wrung to the selected block, one at each end, with the ruled faces in the neutral plane of the selected block, as shown in Figure 2. An interferometric measurement of the combined length is then made, i.e., the interval from center to center of the two graduations. The conversion blocks are then removed and wrung together in the same orientation as when wrung to the selected block, and the interval between graduations is measured by interferometry. This conversion interval length is subtracted from the combined length to obtain the selected block length:

$$L_s = L_c - L_{AB}$$

where L_s is the selected block length, L_c is the measured combined length, and L_{AB} is the measured conversion interval length.

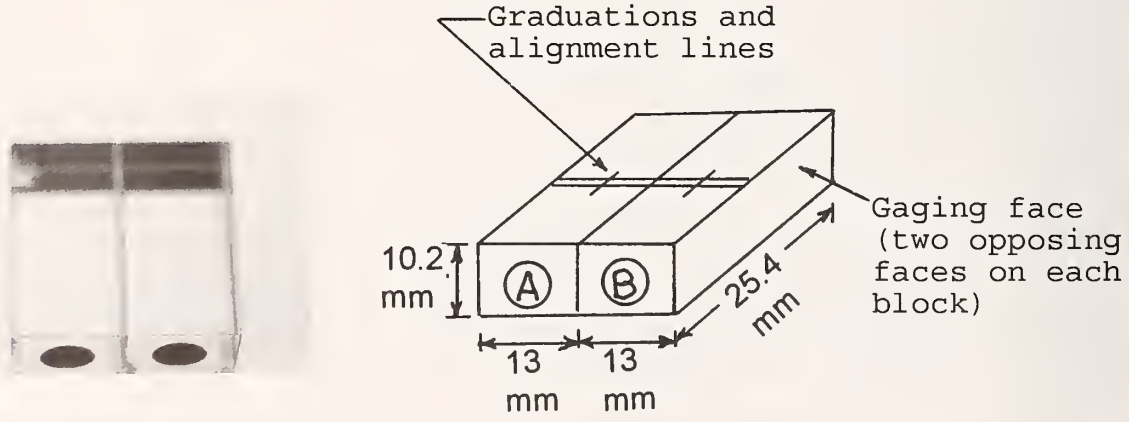

Figure 1. Photo and schematic of conversion blocks.

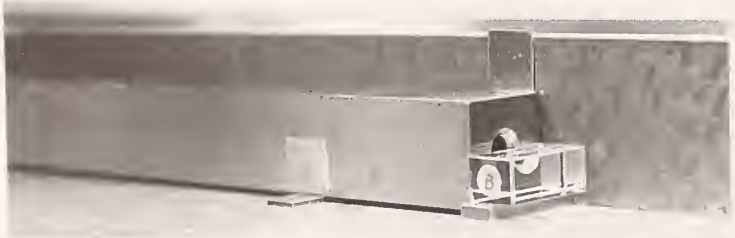

Figure 2. Conversion block wrung to selected block.

2. History of Conversion Blocks

Measuring gage blocks by this method is not new. Conversion blocks were first used at NBS in the late 1950's in preparation for the approaching change in the international definition of the meter from the prototype platinum-iridium meter bar to the wavelength of a specific ^{86}Kr spectral line. This was several years before lasers and dynamic interferometry were invented.

A plan was devised to convert several long gage blocks into line scales with conversion blocks made from commercial blocks modified with rulings at NBS. These long blocks were then measured by comparing them with a group of NBS laboratory standard line scales. By virtue of their known lengths relative to the international prototype meter bar, these laboratory standards were the national length standard at that time. Once the long block lengths were determined, they were used to measure the krypton wavelength by static interferometry. Thus, the krypton wavelength was indirectly measured with the meter as then defined. The meter could then be redefined as a specific number of wavelengths.

The purpose of this exercise was to minimize the change in the actual length of the meter when changing to the new definition. These were difficult procedures: line standard measurements, because of the skill required to make time consuming comparisons using filar eyepiece microscopes and a massive, temperature sensitive, comparator; interferometry, because limited coherence of atomic light sources necessitated stepping up in increments of 200 mm or less to longer lengths.

Based on measurement data from BIPM and several national laboratories, including NBS, the ^{86}Kr wavelength was determined and the number of wavelengths in vacuum was computed for a one meter length. The change in the actual length of the meter has been estimated to be less than 0.2 μm, a worthy achievement for that time[4].

In 1960, the ^{86}Kr wavelength definition of the meter was adopted[4] and interferometry became the official international method of reproducing the meter.

3. The Need for End Standard to Line Standard Conversion

Since 1975, NBS/NIST has used static, single wavelength, laser interferometry to measure its master gage blocks[2]. Single wavelength dynamic laser interferometry has been used to measure line scales since 1964[3]. The HeNe frequency stabilized lasers emit a single wavelength at a nominal 0.633 μm. In static interferometry only the last fraction (called the fringe fraction) of a half-wavelength is observed, as shown in Figure 3. The whole number of half wavelengths (fringes) must be determined by other methods. This means that the length of a gage block must be known to better than 1/4 wavelength (0.16 μm) before it can be measured. Nearly all commercially produced blocks of 100 mm or less are within this

tolerance at the standard temperature of 20 °C. Furthermore, the lengths of NIST master blocks from 100 mm up to and including 500 mm, with many years of history, are known to better than 0.13 μm.

Most unknown blocks can be measured by mechanical comparison[5] with NIST masters to determine the order of interference, as the whole number of fringes is called. Problems arise in some cases, however. For example, in determining the order of interference for odd length blocks and blocks longer than 500 mm having no equivalent master, or even an occasional NIST long block master that gets out of control from rapid secular change or accidental damage. There is also a size limitation because the longest NIST static interferometer is 750 mm. It is in these problem areas that the conversion technique is needed. Measurements up to 1020 mm can be made in the line scale interferometer.

4. A New Conversion Block Design

Previous conversion blocks were commercial 12.7 mm (0.5 inch) gage blocks modified by polishing a side face and machine-ruling graduations on the polished area with a diamond tipped stylus. For the present study, new fused silica conversion blocks were designed with prospects for improved performance.

Fused silica was selected for four reasons: (1) Being transparent, the wringing interface between the selected block and the conversion blocks is visible, thus making it easy to evaluate. (2) High quality chromium lines can be deposited on the side faces for improved measurement precision. (3) Optically lapped fused silica surfaces are very smooth and wring very tightly. This is an important characteristic because the wringing area is small when conversion blocks are wrung crosswise on rectangular selected blocks (steel conversion blocks can be insecure under these conditions). (4) They are lightweight and produce a minimum change in the Airy point support positions.

In a perfect wringing with transparent conversion blocks, the interface will appear as a uniform grey color. Defects in the wring will appear as light areas or, in the worst case, colored areas. These defects can result in errors of 0.025 μm or more.

Steel conversion blocks are wrung with only the "feel" of the wring to judge its quality. Ruling quality on steel conversion blocks, while good, does not match the edge definition, straightness, and contrast of modern chromium lines on a transparent substrate. Two pairs of steel conversion blocks in fairly good condition from the 1950's are extant at NIST. One of these pairs is used in the experiments of section 6.

The fused silica gage blocks used in this study were fabricated by an optical company to NIST specifications for flatness and parallelism of the gaging faces, and for clearness and smoothness of the ruling area. High-quality chrome graduations were added by

a photolithography firm.

5. Measurement methods

5.1 Static Interferometry

One of the long-block interferometers used in the NIST gage block measurement process is shown schematically in Figure 3. A photo of a static interferometric fringe pattern as seen through the exit aperture is also shown. The block is wrung to the steel optical flat (platen). Gage blocks are particularly suited to this measurement technique because the optically finished upper face and the optical flat that forms the extension of the lower face serve as mirrors in the interferometer. Together, with the reference mirror in the diagram, these surfaces form an interferometer that makes the interference phenomenon possible. A length measurement is made from the plane of the optical flat to the gage point on the top face. This length includes the wringing film that exists between the block and the platen. Blocks are frequently used in wrung combinations (stacks). When combined, each block in a stack includes one wringing film. Gage block length is defined[6,7] as the distance from the gage point to the plane of the optical flat to which the block is wrung. The definition fits both the widely used stacked condition and the interferometric measurement technique.

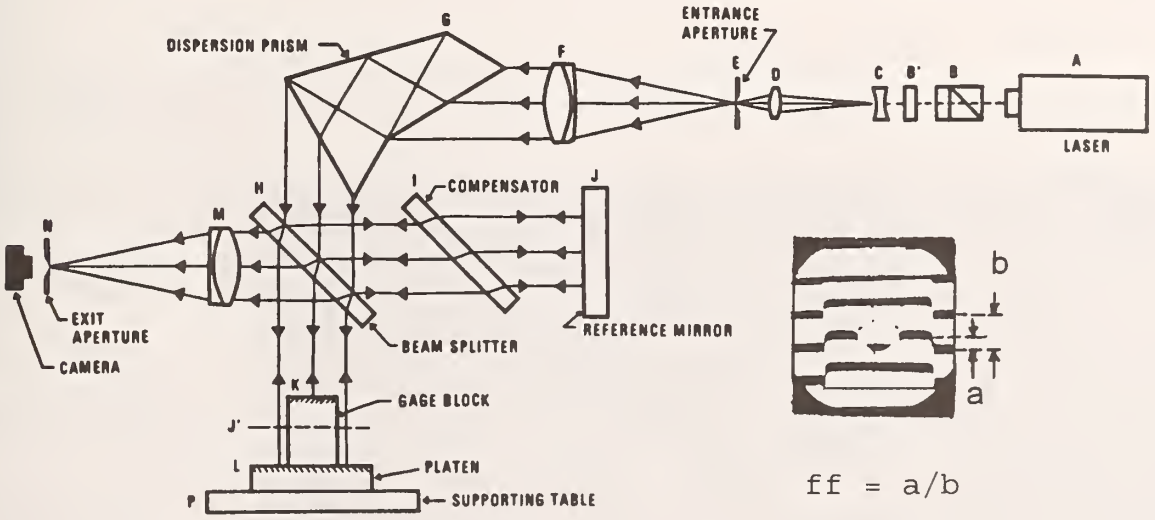

Figure 3. Gage block interferometer schematic with photo of a fringe pattern as seen through exit aperture.

Two fringe patterns are formed in this interferometer: one on the platen and the other on the gage block upper face. The offset between the two patterns is called the fringe fraction, and it is the ratio a/b in Figure 3. It is always measured with the interferometer adjusted so that one gage block fringe passes through the gage point to ensure that the defined length from the platen face to the gage point is measured. On a rectangular block

the gage point is at the center of the face. On a Hoke type block, it is halfway between the center hole and the side of the block where the size is marked.

In the NIST measurement process, a stabilized and calibrated laser is the wavelength source. The fringe fraction is the last part of a half wavelength in the block length. It must be added to the whole number of half wavelengths (fringes) in the block length. This whole number, called the order of interference, must be determined by a secondary method, i.e., by mechanical comparison with a calibrated master block or by gage block to line scale conversion. To visualize the fringe fraction origin, imagine that the gage block is infinitely compressible and the upper face can be pressed down to the plane of the platen. At this point the block and platen fringes are coincident. Then imagine that the block face slowly grows to its original height and that the fringes that flow past the gage point as it grows are counted while the platen fringes remain fixed. This count is the whole number of half wavelengths. The fraction is added to the count to get the actual total length. The total is converted to millimeters or inches by multiplying it by a "fringe multiplier." This multiplier is composed of one-half the wavelength corrected to observed air ambient conditions of temperature, pressure, CO_2 content and humidity. A factor is also included to correct block length to 20 °C from observed temperature using the block thermal expansion coefficient.

5.2 Dynamic Interferometry

In preparing a selected block for the line scale measurement, the conversion blocks are wrung to its end faces. The conversion blocks are precisely positioned, both horizontally and vertically, so that the graduations are on the central axis of the selected block. The wringing interface is examined for flaws and re-wrung until a minimum of flaws are seen. Deburring the gaging faces with a deburring stone may be necessary to improve surface conditions.

A schematic of the NIST line scale interferometer and a photograph of a gage block mounted for measurement is shown in Figure 4. A converted gage block is mounted horizontally on the carriage and the graduations focused in the photoelectric microscope field. Airy point support is used because it maintains the gage block end faces parallel to the degree that they are parallel in the vertical position. The Airy points of the gage block are, for practical purposes, the same with or without the fused silica conversion blocks attached because of their light weight. When steel conversion blocks are used, Airy points must be recomputed. Once temperature has stabilized, the distance between the graduations on the conversion blocks is measured by fringe counting. Both the whole number and the interpolated fractional fringe are accumulated in the counter. This count is converted into length units (millimeters or inches) by the computer-controller in a similar manner to static interferometry. Several passes are made up and back. These are averaged to produce a length value at the standard

temperature of 20 °C. Conversion blocks are re-wrung on the selected block two or more times and repeat measurements made. The average of all values is the combined length.

The conversion blocks are wrung together, precisely aligned and mounted in the line scale interferometer for measurement in the same manner as the combined length. Repeat wringings and measurements are made and averaged to give the conversion interval length. Subtracting conversion interval length from combined length yields the selected block length.

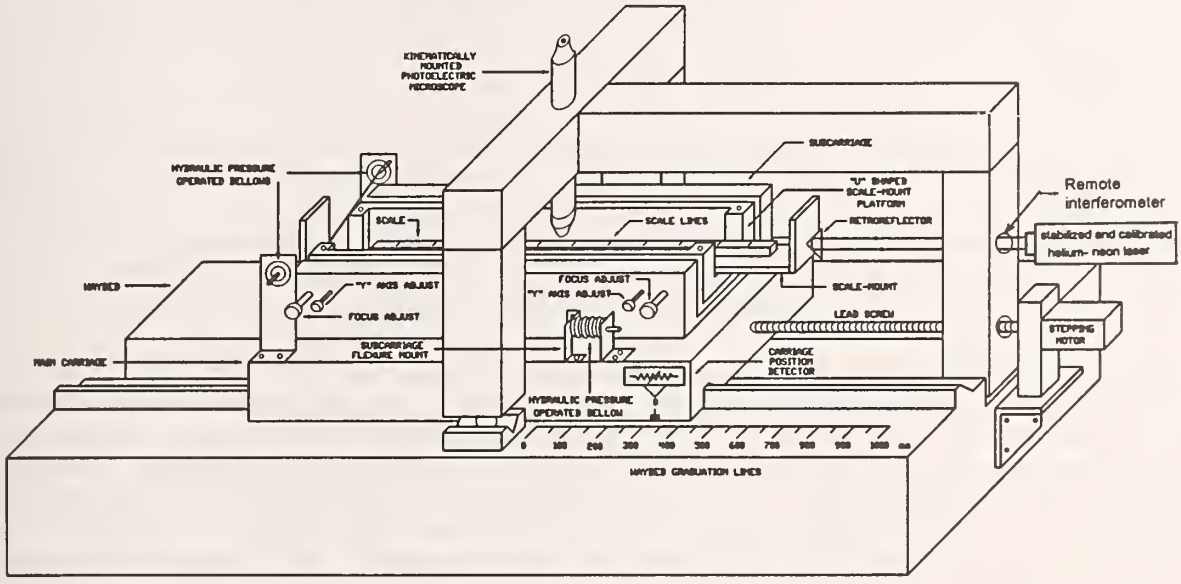

Figure 4. Schematic diagram of the NIST line scale interferometer and a photo of a long rectangular gage block mounted for measurement.

6.Sources of Differences in Results

There are differences in the principles of these two measurement methods that will inevitably produce small differences in results. Five factors that can affect the degree of agreement between the two methods are: (1) flatness of the gaging faces, (2) parallelism of the gaging faces, (3) conversion block alignment, (4) the presence of two wringing films in the conversion process and only one in the static interferometric measurement, and (5) static measurements are vertical and dynamic measurements are horizontal so the influence of gravity on the block length is different. Corrections for most of these factors can be derived and applied.

6.1 Geometry of the Selected Block

If a block of rectangular cross section deviates in flatness across its width at both ends as in Figure 5 (left) the effect will be negligible. This is because the gage point is at the center where the static measurement is made and coincident with the graduations in the conversion method. Gaging faces are generally symmetrically convex in all but very thin blocks where warping is present.

In a Hoke type block with a flatness deviation across the width at both ends as in Figure 5 (right) there will be a difference because the gage point is not at the point of maximum length where the conversion measurement is made. It is offset to a point halfway between the hole and the block edge. This can be compensated by measuring the difference in elevation between the two points and subtracting it from the conversion measurement. At the end opposite the gage point there will be no difference between the two methods because both conversion block and platen will be wrung to the area of maximum length.

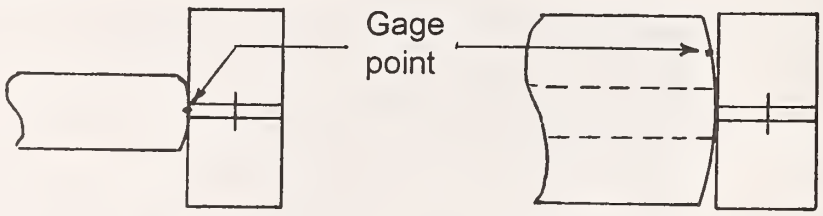

Figure 5. The effect of flatness deviations on the measurement of rectangular (left) and Hoke (right) types of selected blocks.

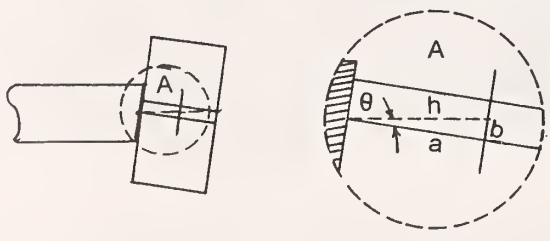

Figure 6. The effect of parallelism deviation on the measurement of a rectangular selected block.

Figures 5 and 6 show flatness and parallelism deviations which are greatly exaggerated for illustrative purposes.

Small (0.05 μm or less) deviations in parallelism of the gaging faces will create only a very minor problem as shown in Figure 6. A parallelism error, either across or along, will produce a lengthening in the distance from the gaging face of the selected block to the graduation on the conversion block. The amount of lengthening is the difference, h - a, and this difference is very small because side a is short (6.5 mm) and angle θ is small (0.02 s) for an 0.05 μm parallelism deviation.

Large flatness and parallelism errors, of 0.10 μm or more, add to measurement uncertainty in mechanical intercomparisons and static interferometry. These errors also add to the uncertainty in using gage blocks by affecting the geometry of stacks. Blocks with poor geometry should be replaced.

6.2 Geometric and Graduation Quality of the Conversion Blocks

The fused silica conversion blocks were required to meet close tolerances for flatness and parallelism: 0.025 μm across the width and 0.050 μm along the length of the faces. When received from the manufacturer these blocks were even better than this. Such close tolerances will not cause significant measurement errors. In addition, the high quality chrome graduations ensure excellent line setting precision and the longitudinal alignment tracks running to the edges of the graduated faces make aligning the blocks relatively easy.

6.3 The Second Wringing Film

Wringing film thickness is difficult to measure and can vary from block to block and wring to wring by as much as 0.064 μm. The accepted average wringing film thickness value of 0.025 μm is used here to correct the conversion method measurements.

6.4 Length Change from Horizontal to Vertical

Gravitational force will shorten a block when changed from a horizontal to a vertical position. Gage block lengths are reported in the vertical position so a negative correction must be made to the horizontal length value. The equation for this correction is:

$$\delta = \frac{\omega L^2}{2\,AE}$$

where δ = amount of shortening
ω = weight per unit length of the block
L = total length of the block
A = cross sectional area
e = Young's modulus of elasticity

7. Experimental tests

7.1 Objectives

The general objective is to test the theoretical advantages of the new fused silica conversion blocks. There are three subdivisions to the general objective: (1) determine the degree of agreement between the fundamental interferometric method (static interferometry) and each of the two conversion block methods, (2) determine the measurement precision of each method and (3) judge the relative ease of use and durability of the conversion blocks.

7.2 Equipment

SELECTED BLOCK
Nominal size:10 inches (254 mm)
Identification No. 2306
Material: steel
Coefficient of thermal expansion: 10.6 x 10^{-6} m/m/°C
Flatness and parallelism deviations: 0.050 μm or less

INTERFEROMETERS:
Static: Kösters type, gage block interferometer
Dynamic: NIST Line Scale Interferometer

CONVERSION BLOCKS:
Fused silica pair: A and B
Steel pair: K and M

7.3 Procedure

The first step is to measure the interval between the graduations on the steel and fused silica conversion blocks. This requires careful wringing and alignment of each pair. Alignment is done on a bench microscope having a crosshair in the eyepiece and a moveable stage. The interval is then measured in the line scale interferometer. This process is repeated several times to generate redundant data for statistical analysis. The mean value for each pair is subtracted from the total length each time a selected block is measured with the conversion blocks attached.

A single high quality gage block was selected for measurement by conversion and static interferometry. Measurement data on this block will determine comparability of the methods. The block chosen is a 254 mm (10 inch) Hoke type steel block. It has excellent flatness and parallelism of the gaging surfaces, fine surface finish and a square cross section which provides a large wringing area for attaching conversion blocks.

Wringing conversion blocks to the selected block must be carefully done to ensure that the graduations and their alignment marks are coincident with the central axis of the selected block. This is accomplished on a surface plate by using a straight edge and gage block spacers as shown in Figure 7.

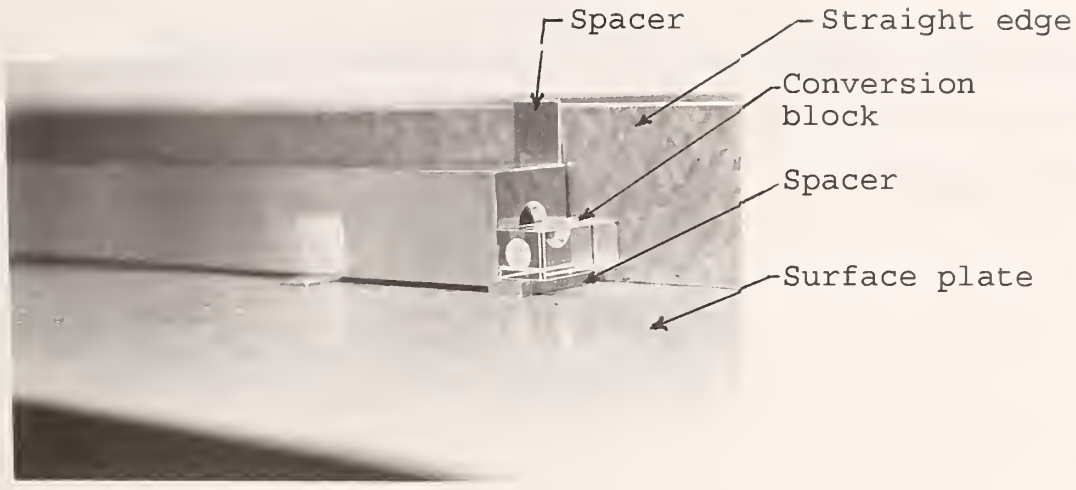

Figure 7. Aligning a conversion block with gage block spacers, using a horizontal surface plate and a straight edge.

In addition to data on the 254 mm block, data on two special end standards are included to illustrate typical conversion measurement results from the NIST gage block calibration program. These two bars were measured to establish the interference order for static interferometry measurement. They are:

A "16 inch" (406.4 mm) bar with a round cross section.
An "18 inch" (457.2 mm) bar with a round cross section.

Both bars have good geometry: 0.064 μm or less flatness and parallelism errors.

7.4 Results

Three estimates of measurement repeatability are used in the following tables of measurement results: (1) σ, the standard deviation, the usual measure of repeatability, (2) σ^2, the variance, which can be used in a statistical technique called the analysis of variance to separate the sources of variability, and (3) 2σ, which is an estimate at a 95% confidence level. The latter predicts that, based on present performance, additional measurements will agree 95% of the time with the current mean within the limits of the $\pm 2\sigma$ value. Subscripts after σ identify the measurement being evaluated: g for the conversion block graduated interval measurement (Table 1), s for selected block measurement (Table 2), and w for measurements made with a single wringing (Table 3).

A summary of the graduated interval measurements on the two pairs of conversion blocks is shown in Table 1. In Table 2, measurement results on the selected experimental block are summarized.

Table 1.
Graduated interval length and measurement precision

	AB	KM
Interval length at 20° C.	12.997482 mm	10.108339 mm
σ_g	0.036 μm	0.066 μm
σ_g^2	0.0013 μm^2	0.0044 μm^2
$2\sigma_g$	0.072 μm	0.132 μm
Number of wrings, n	8	8

Table 2.
Measurement results on the 254 mm selected gage block

	Dynamic Interferometry		Static Interferometry
	254 mm block with A & B	254 mm block with K & M	254 mm block
MEASUREMENTS (lengths at 20° C.)			
Mean length	254.000404 mm	254.000406 mm	254.000376 mm
σ_s	0.030 μm	0.068 μm	0.020 μm
σ_s^2	0.0009 μm^2	0.0046 μm^2	0.0004 μm^2
$2\sigma_s$	0.060 μm	0.136 μm	0.040 μm
n	8	8	8
CORRECTIONS			
Dev. from nom.	0.404 μm	0.406 μm	0.376 μm
-one wring film	-.025	-.025	
Horiz. to vert.	-.012	-.012	
Corrected value	0.367	0.369	0.376
FINAL LENGTH	254.000367 mm	254.000369 mm	254.000376 mm

Table 3 shows precisions for repeated measurement of: (1) the length, measured by static interferometry, for a single wringing of the 10 inch block, (2) the combined length, measured in the line scale interferometer, for a single wringing of conversion blocks A and B to the selected block, and (3) the same with conversion blocks K and M.

Table 3
Measurement repeatability for a single wring

	Dynamic Interferometry		Static Interferometry
	254 mm block with AB	254 mm block with KM	254 mm block
σ_w	0.005 μm	0.007 μm	0.009 μm
σ_w^2	0.00003 μm^2	0.00005 μm^2	0.00009 μm^2
$2\sigma_w$	0.010 μm	0.014 μm	0.018 μm
n	8	8	8

The first question in considering the data in these tables is how well do the three measurement methods agree? They agree remarkably well (within 0.009 μm) as shown in Table 2. But, as previously mentioned, the correction for wringing film thickness could not be directly measured so the generally accepted value of 0.025 μm is used.

The second question is which of the two conversion block methods produces the least measurement variability? An answer comes from the statistical measures of repeatability which say that fused quartz is the most precise. This is not only in the measurement of the 254 mm block (Table 2), but also in the measurement of the line spacing in multiple wringings (Table 1) and in a single wringing (Table 3). The graduations on the fused silica can be read with less variability and their gaging surfaces can be wrung with less variability than the steel blocks.

Analysis of variance can reveal other characteristics of these measurements. In the static interferometric measurements of the 10 inch block, variance from the single wringing in Table 3 can be subtracted from total variance in Table 2:

$$\sigma_r^2 = \sigma_s^2 - \sigma_w^2 = 0.0004 - 0.00009 = 0.00031 \ \mu m^2$$

Standard deviations in Table 3 reflect all measurement variability except that from repeated wringing. By subtracting variance σ_w^2 from variance σ_s^2 in the computation above, the wringing variability is separated. The wringing variability standard deviation, σ_r, and the $2\sigma_r$ prediction of the bounds of this variability in additional static interferometry measurements of the 254 mm block become:

$$\sigma_r = \sqrt{0.00031} = 0.018 \ \mu m, \text{ and } 2\sigma_r = 0.036 \ \mu m$$

The same computation, again using the data in Tables 2 and 3, produces estimates of the variability of wringing blocks A and B to the 254 mm block, and the variability of wringing blocks K and M to the 254 mm block:

σ_r = 0.029 μm, and $2\sigma_r$ = 0.058 μm for A and B

σ_r = 0.067 μm, and $2\sigma_r$ = 0.134 μm for K and M

Some conversion block wringing variability is produced by gaging surface conditions. The steel blocks have been used enough over the years to roughen the surfaces so they do not wring as tightly or consistently as they once did. Stoning the faces will no longer restore them to optimum condition; only relapping them can do that. On the other extreme, the fused silica blocks have such smooth surfaces that they tend to wring together too tightly and must be treated with extra wringing film material to prevent optical contacting. This condition is gradually improving as they are used.

7.5 Additional measurements

In the course of this experiment two long gage blocks from private sector customers were measured by conversion to establish the interference order for a static interferometric measurement. Results of these measurements are shown in Table 4 as examples of routine conversion measurements in the NIST gage block calibration program. Each block was wrung twice for both conversion and static interferometry.

Table 4
Results of routine calibration results for NIST customers

Block Description	Conversion Measurement Using A and B (mm)	Static Interf. Measurement (mm)	Difference (μm)
"16 inch" (406.4 mm)	406.399322	406.399355	-0.033
"18 inch" (457.2 mm)	457.200048	457.200041	0.007

8. Measurement uncertainty

The analysis presented here has stressed measurement repeatability, the degree of agreement between the two types of conversion blocks, and the degree of agreement between the dynamic and static interferometry processes. Although this is sufficient to meet the objectives of this paper, it is worthwhile to discuss measurement uncertainty briefly.

The two measurement processes involved, static gage block interferometry and dynamic line scale interferometry, are well documented by long standing measurement assurance programs[5,8].

International and NIST policy requires expanded uncertainty, U, to be stated as follows:

$$U = ku_c$$

where k is the coverage factor, and combined standard uncertainty, u_c, is

$$u_c = \sqrt{(u_i^2 + u_j^2)}$$

where u_i is the standard uncertainty arising from random effects and u_j is the standard uncertainty arising from systematic effects in the measurement process. Coverage factor k is assigned a value of 2 which provides a confidence level of approximately 95% in the expanded uncertainty.

Applying these rules to the data in this paper results in the following evaluations of uncertainties:

Taking the random effects seen in the experiment (Table 2, σ_s) and the systematic effects documented in reference [5] into account, the uncertainties for the static interferometry measurements are:

$$u_c = \sqrt{0.020^2 + (0.05 \times 0.254)^2} = .024\ \mu m$$

and

$$U = 2(0.024) = 0.048\ \mu m$$

Using the same analysis on the dynamic interferometry measurements, with random effects in the measurements using conversion blocks K and M (fused silica), and systematic effects documented in reference [8], the uncertainties are:

$$u_c = \sqrt{(0.030^2 + (0.05 \times 0.254)^2} = 0.033\ \mu m$$

and

$$U = 2(0.033) = 0.066\ \mu m$$

The systematic component, 0.05 μm (u_j), is a length dependent factor expressed in parts in 10^6. That is why it is multiplied by the length measured, in this case 0.254 m, to scale it to this measurement. Random error comes directly from analyzing the measurement data and thus needs no scaling.

Another valid approach to estimating uncertainty is to measure a quantity by two independent methods and compare the results. Static and dynamic interferometric methods are not fully independent, because they share the same sources and magnitudes of systematic error. This may explain, in part, why they agree so well in Table 2. The mean of the two dynamic values is 254.000368 mm while the mean static value is 254.000376. This is a difference of only 8 nm as contrasted with uncertainties of 48 and 65 nm by the first method. The best values for uncertainty are probably between the two methods, since both analyses are based on a relatively small number of observations. However, this does not change any of the conclusions in the next section.

9. Conclusions

Theoretical advantages of fused silica conversion blocks over the steel variety have proved to be true in experiments presented here. Advantages and one disadvantage are as follows:

(1) Chromium graduations on fused silica conversion blocks yield better repeatability than the graduations on the steel conversion blocks (see Table 3).
(2) Wringing repeatability is better for fused silica blocks (see Table 1).
(3) Measurement repeatability on the 254 mm selected block is better with fused silica blocks than with steel blocks (see Table 2).
(4) Light weight, wringing interface visibility, superior surface finish and excellent geometry (flatness and parallelism) are judged to make fused silica blocks easier to wring to the selected block. Light weight also means that the effect on the Airy support point positions is negligible.
(6) Durability is one potential disadvantage of fused silica. Both steel and fused silica gaging surfaces will become scratched with use, but the latter tends to chip easily. Chips on the gaging faces may leave sharp edges that can scratch other surfaces during wringing. Edges of some chips can be rubbed with a deburring stone to reduce sharpness. Block A sustained a minor chip, but its sharp edge was reducible.
(7) Some of the fairly large wringing variability in both pairs of conversion blocks is caused by the condition of the gaging surfaces. The gaging faces of K and M show signs of wear. One face of K (a face not used in these experiments) will not wring, and stoning will not restore it. On the other extreme, the faces of A and B are so perfect that a heavier than normal grease film is needed to prevent optical contacting when they are wrung together.

It is noteworthy that all of the measurements of the 254 mm block with both pairs of conversion blocks qualify for determining the order of interference, i.e., they are within ½ fringe (0.16 μm) of the actual block length. The 3σ prediction, however, for the use of K and M is that at some point in making additional measurements there will be outlying values (see Table 2 where $3\sigma_s$ = 0.204 μm).

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Acknowledgments: The author wishes to thank Group Leader Ralph Veale for his support in this project, and to both Dr. Theodore Doiron and William Penzes for very helpful discussions and ideas that led to its successful completion.

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